Geodynamics monitorization using wireless sensor networks

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AbstractWireless sensor networks are a cheap and versatile solution for monitoring various environments and elements of an environment. There exists a number of such applications used worldwide to monitor areas in which human access is hard or near impossible. The issue with these applications is that they are mainly used by government organizations or for research purposes. They seldom focus on using the data in the interest of safety for the population, such as warning them of natural disasters or assessing the risk of damaged areas left in the wake of a natural disaster. The solution we propose in this article is a low power, low cost wireless sensor which is used to monitor earthquakes and the status of urban structures exposed to earthquakes or other sources of vibration in order to prevent possible disasters.

Keywords: Wireless Sensor Networks, Geodynamics, Earthquake monitoring, Low power

1. INTRODUCTION

In recent years, wireless sensor networks have been used more and more often as a cheap and easy to maintain monitoring system. Wireless sensors are adequate tools for monitoring various environments due to a series of characteristics such as: low power consumption which increases autonomy and helps reduce the node size (no need to attach large batteries), the possibility to attach energy harvesting modules which further help to increase their autonomy and the ability to mount numerous sensor peripherals on a small surface.

Since these sensors communicate via wireless networks, they are ideal tools to use in monitoring remote or otherwise hostile environments such as: underground caverns, ocean floors, volcanic mountain ranges, etc. Another field in which wireless sensors would represent a good monitoring solution is geodynamics. Using such a network, it could be possible to predict natural phenomena such as earthquakes, tsunamis, landslides and volcanic eruptions much faster and with increased precision regarding magnitude and the time of the event. Also, such a solution may prove to be cheaper and more flexible than existing installations deployed for performing these tasks.

Delving even deeper into the utility of such an application, we can take into account that whenever a phenomena amongst those mentioned earlier occurs, the areas which often suffer damages are cities and towns. A good use for a wireless sensor network would be to mount it around cities and on buildings inside the city situated in such danger zones. Thus, whenever an earthquake or other natural disaster occurs, authorities can respond faster and reduce the damage, both material and human lives.

In this paper, we propose a wireless sensor network solution for monitoring earthquakes. The nodes can be mounted on buildings and they will monitor the vibration of the building as well as various other parameters (air pressure, temperature, etc.). Once calibrated to the "normal" values of the parameters, whenever these parameters go over a threshold value, a system is notified that there is a possible risk of an earthquake happening. More so, this system can be used to determine if a building is exposed to deterioration due to external factors such as proximity to construction site, roads frequented by heavy load trucks, etc.

In the Architecture section we shall present how the SparrowV4 sensor's hardware and software components are designed and interconnected. Then, in the Experimental section we present the laboratory tests which were ran in order to determine the viability of these sensors. The Results section shall analyze the data acquired during the tests and show that the SparrowV4 wireless sensor nodes are reliable. Finally, in the Conclusions and Future Work sections, we discuss how the sensors can be further improved with new hardware components.

2. RELATED WORK

Applications which monitor geodynamics using wireless sensor networks have been attempted before. However, most have been used to monitor volcanic activity, tsunamis and building structure integrity but there are seldom any references of attempts to monitor earthquakes directly using wireless sensor networks.

Researchers from Singapore, China and the USA have published a paper describing their implementation of an improved algorithm for WSNs in order to monitor volcanic activityLiu et al. (2013). This new algorithm, using data gathered from the sensors, would determine as accurately as possible and in real time the arrival of primary seismic wavesBen-Menahem and Singh (2012) which are produced prior to a volcanic eruption. Although not directly focused on earthquake monitoring, this research provides a starting point for further research and improvements in this area.

Another implementation using WSNs is presented in an article by N. Meenakshi and Paul Rodrigues Meenakshi and Rodrigues (2014) and focuses on tsunami monitoring using WSNs. They propose a network composed of 3 types of nodes: sensors, commanders and barriers. The sensors are dispersed underwater to monitor the water pressure. This data is sent to commanders which process it and determine if there is any specific area in danger of being hit by an incoming tsunami, determined by the variations in pressure. If there is any danger, the barrier sensors in that area are notified to activate the barriers.

One more direction in which geodynamics monitoring WSNs have been used is structural integrity of buildings Torfs et al. (2013). Especially in urban areas, buildings are often exposed to vibrations caused by various factors: heavy vehicles such as public transport or cargo trucks, proximity to construction sites, etc. In time, such buildings deteriorate and become a danger because they are prone to collapsing. Using such sensors to monitor the vibrations they are exposed to, damage can be prevented by determining if a building is prone to collapsing and if it poses a threat to people and other structures in the area.

3. ARCHITECTURE

3.1 Hardware

The Sparrow v4 wireless sensor nodes are custom designed for use in various research projects. They are designed as a single PCB board which hosts all of the major components, such as: controller, RF module, power supply and sensors. The main the main processing unit of the Sparrow v4 nodes is an ATmega128RFA1 micro controller, which hosts an on-chip transceiver Atmel and the. The low power, ATmega128RFA1 microcontroller is connected to all of the node's sensors and its main function is to process the data received from them and pass it on via the RF transceiver. The transceiver is a low power wireless transmission chip capable of sending signals to distances of up to a few kilometres, according to the official datasheet **?**. It also provides an AES-128 compatible security module for data encryption and decryption.

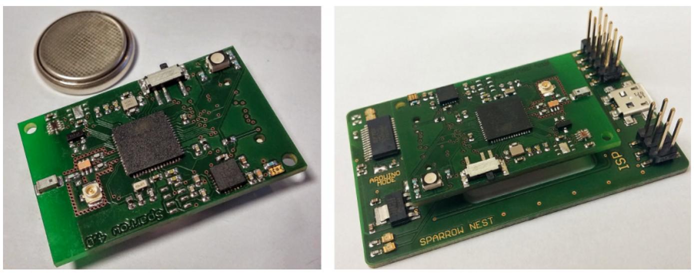

Figure 1. SparrowV4 wireless sensor nodes

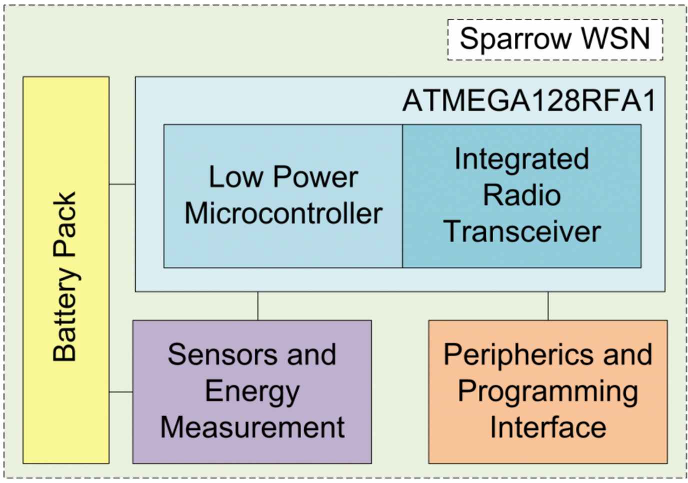

Figure 2. SparrowV4 hardware architecture

In order to monitor its environment, the Sparrow v4 wireless sensor node relies on 3 main sensor peripherals. The first is an Si7020 humidity and temperature sensorLabs with incorporated ADC unit. The measurement resolution for relative humidity measurements can vary between 8 and 12 bits, while the resolution for temperature measurements varies from 11 to 14 bits. The second sensor is an MPL3115A2 Xtrinsic altimeter which can measure pressure and altitude. This sensor also has an incorporated ADC unit and can measure both altitude and pressure with a precision of up to 20 bits. The final sensor mounted on the Sparrow v4 and the most important for earthquake and vibration monitoring is the LSM9DS0 IMU(Inertial Measurement Unit)Adafruit. This chip has 3 channels for linear acceleration measurement, 3 channels for angular rate measurement and another 3 channels for magnetic field measurement. All data measurements are performed at a 16 bit resolution. From this last sensor, the metric used by the presented application is the linear acceleration (measured in Gs). All of the aforementioned sensors are connected to the microcontroller via a two-wire interface. Each of the has a different slave address so it is possible for the master, the ATmega128RFA1 controller, to communicate with all of them without interference from the others.

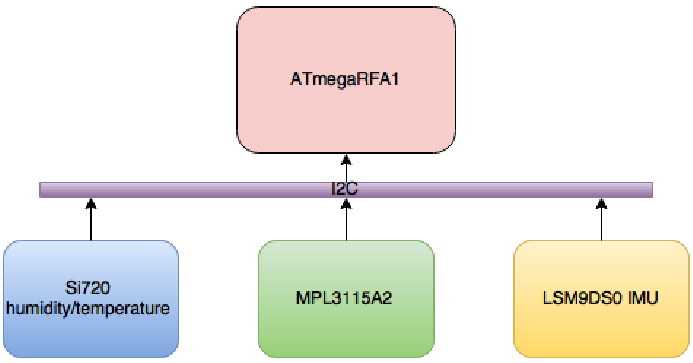

Figure 3. Sensors connected on two-wire interface

All the components on the Sparrow v4 node function at a maximum supply voltage of 3.3V. The node can be powered in 2 ways: either from a lithium polymer battery cell or via an USB port. When powered via USB, a linear

DC regulator is used to drop the supply voltage from the 5V of the USB line to the necessary 3.3V.

The nodes can be easily programmed from a computer using the specially designed programming interface. This interface represents a separate piece of hardware on which the Sparrow nodes can me mounted. The programming board is built using an FTDI chip which can transform RS-232 transmissions to USB signals. This means that the nodes can be programmed using a normal USB connection and no other special programming cable or component is required.

3.2 Software

The Sparrow v4 wireless sensor nodes run an ArduinoArduino compatible firmware. This allows the programmer to easily import and use open source Arduino modules for each peripheral. Another advantage of using an Arduino compatible firmware is that it ensures the code is compatible with multiple platforms and can be easily modified, upgraded or ported to similar hardware. For development, the Arduino IDE is used because it provides access to predefined libraries for peripherals such as serial line, two-wire interface and ADC. It is also available on a wide variety of operating systems which makes code modifications and firmware updates easier to implement.

The firmware which runs on the Sparrow v4 nodes operates in two steps. The first step is a calibration phase, which starts running when the sensor is first turned on. This will determine the default values for each of the 3 accelerometer axes for the current position of the node. Once this step is completed, the node enters its second step in which it will continuously function until it is turned off. During this period, it harvests data from the accelerometer and sends it towards a designated gateway. The gateway shall always be connected to a server which is capable of plotting and analysing the data. The gateway communicates with this server by means of a serial interface.

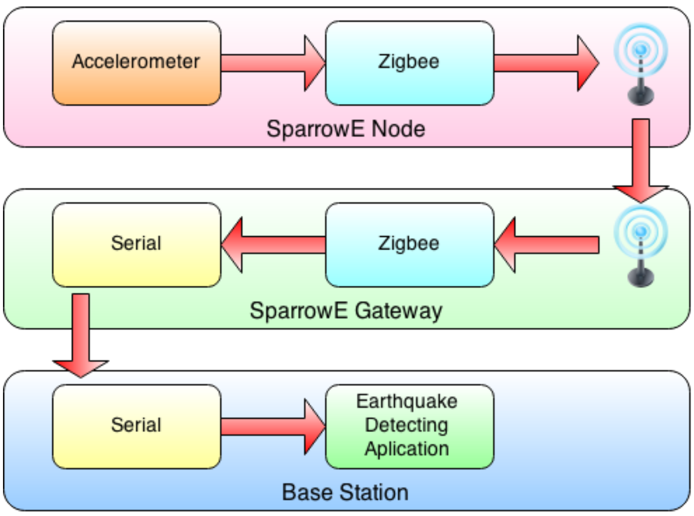

Figure 4. Software architecture connections

The accelerometer on the Sparrow v4 node is configured for a +/-2G linear acceleration rate and operates at an Ouput Data Rate of 50 Hz. The raw data from the 3 axes is translated by the ATmega128RFA1 microcontroller into gravitational scale and then is normalized.

This approach will generate a value of 1G when the node is kept still, in its calibrated position. When the surface starts vibrating, the value will start varying above or bellow the reference value of 1G. The calculated data is gathered in sent periodically by the controller to the gateway. Node identification data is also added to the sent packets. The gateway is able to collect data from multiple nodes and send it to the base station through the aforementioned serial connection, which is configured at a baud rate of 1Mbps. The base station is responsible for saving and interpreting the data. It is considered that a node has detected an earthquake if the values oscillate strongly over the 1G reference value, reaching peaks at 2G+.

3.3 Low Power

The goal of the sensors is to monitor earthquakes and similar phenomena over prolonged periods of time. We must ensure that the Sparrow v4 sensors function in a low power state and capable of running for prolonged periods of time. This problem is tackled mainly at the software level. At the hardware level, while the components of the sensor are selected with regard to power consumption, their power consumption is still relatively high considering the target autonomy of the Sparrow v4 sensor.

In order to overcome this, the firmware is designed to keep the controller in a sleep state and wake it up periodically to read the accelerometer data. This technique is similar to clock gating and it is done with the use of a RTC (Real Time Clock). The AtmegRFA1 controller on the nodes offers the ability of using the Timer/Counter2 peripheral as a real time clock source with an external 32768hz crystal oscillator. The reason why a real time clock is used to implement this mechanism is that even while the controller is in sleep mode, this peripheral is still active and it will generate interrupts at certain time intervals, as configured by the programmer. When the controller receives such an interrupt, it will wake up and perform any designated operation after which it is put back to sleep and the entire process starts again.

By using this technique, the data from the accelerometer is read and sent to a base station once every half of second instead of once every hundred milliseconds. By doing this, the battery is preserved for much longer, as the controller and the transceiver operate for shorter periods of time. The only component with 100 percent uptime is the accelerometer. According to the datasheet of each individual component, the accelerometer's consumption in normal mode is 350 micro amps, while the ATmegaRFA1's consumption is 4.7 milli amps in normal mode and 0.2 micro amps in sleep mode. In theory, the sensors should never have an average power consumption higher the 1 milli amp. An example of the actual power consumption over the course of 1.1 seconds of activity can be seen in figure 5.

While the controller is put into a sleep state, the accelerometer is always powered on and functioning. The LSM9DS0 chip comes with 192 bytes of memory where it

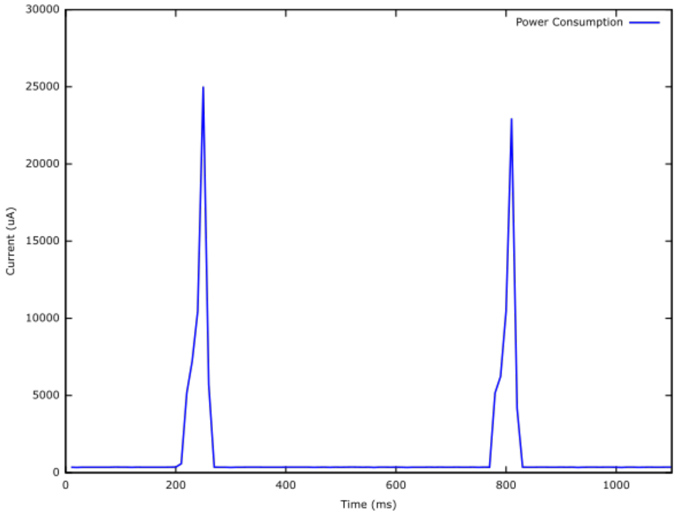

Figure 5. Power consumption example

can store the data it reads. This allows the controller to always read the latest data from the accelerometer while relaying the oldest to the base-station. Because we use a 50Hz ODR for the accelerometer, the FIFO queue will fill in less then a second. So every other 500 milliseconds we read the data from the FIFO buffer, we process it and send the normalized values to the base station. By doing so, the sensor nodes will be prompt when it comes to detecting events but, at the same time, they will maintain a low power state by transmitting data in smaller quantities over longer periods of time.

With this approach, we increase the autonomy of the Sparrow v4 sensor node while, at the same time, making data easier to handle by the plotting and interpretation software running on the base station.

4. EXPERIMENTAL SETUP

In order to test the accuracy and capability of the Sparrow v4 wireless sensor nodes, we have built a shake table in order to simulate the movements of a building during an earthquake. The purpose of the experiment is to see if the Sparrow v4 nodes can detect the main waves which are felt during an earthquake, P-waves and S-waves.

P-waves stands for Primary Waves and is a type of seismic wave produced when an earthquake occurs. Amongst seismic waves, it has the highest velocity, making it the first wave which is recorded by conventional seismographs. This wave is formed by alternating compressions and rarefactions of the material and its mode of propagation is always longitudinal. The other type of wave which can be recorded during an earthquake is the S-wave which stands for secondary or shear wave. S-waves move in a transversal manner through the body of an object, thus resulting in motion which is perpendicular to the direction of wave propagation.

The experimental setup tries to emulate the effects of these waves on a tall building which has Sparrow v4 nodes mounted on its sides. The purpose of the experiment is to see how accurate the data harvested by the IMU is and how the amplitude of the movement varies from floor to floor.

Figure 6. SparrowE wireless sensor nodes mounted on the experimental rig

In order to perform the experiment, an experimental rig was built. This rig uses a movable frame as its base, and a tall, layered shelf mounted on top of it. The frame is composed of two individual planes which are moved individually by two DC motors. One plane produces left-right movement, while the other moves the shelf forward and backward. The planes are connected to the corresponding motor via a crank whose length can be adjusted, thus giving the ability to control the amplitude of the movement. Smaller amplitudes will result in sudden and violent shakes while higher amplitudes will allow the shelf to sway more. The schematic of the movable frame is presented below:

During the experiment, we harvest the accelerometer data from the Sparrow v4 sensors' IMU at various movement speeds. The movement speed is controlled by the supply voltage on the motors. The supply values we chose for the experiment are 2V, 4V, 7V and 12V, simulating low, medium, high and extremely high vibrations.

5. RESULTS

The tests were conducted using 4 nodes connected to a gateway. The nodes were placed one on each shelf of the experimental rig in order to see how the height of the shelf affects vibrations, similar to a tall building. The nodes were securely mounted and calibrated until they were stable enough to not be affected by small vibrations which could corrupt the actual data. This would also apply to a

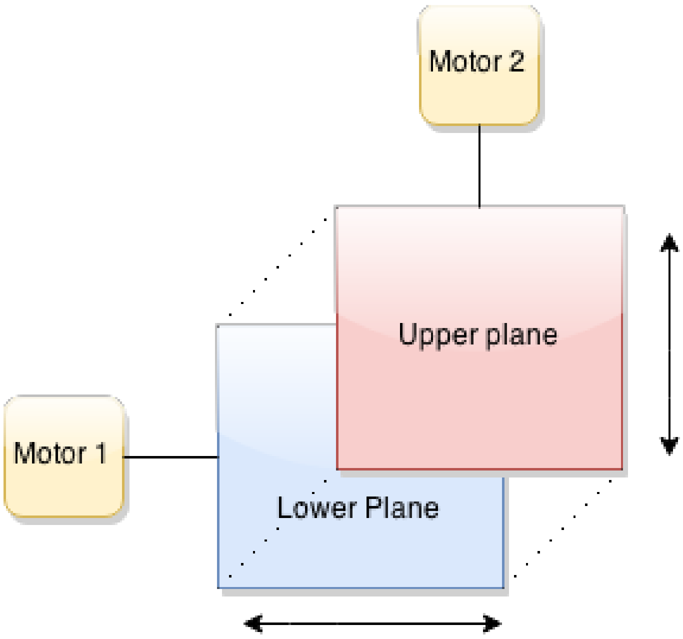

Figure 7. Experimental rig moving frame diagram

real world scenario, where the nodes would need a sturdy mounting place to properly sense relevant vibrations in the structure of the building.

We have conducted 4 test runs by setting the supply voltage for the shake table's motors at different values. The shake table was powered on for 3 seconds during each test run. The first test is performed with a still table to verify just how sensitive the sensor nodes are. Then, we simulated 3 types of vibrations generated by different movements: small vibrations obtained by swaying the test table, medium vibrations obtained by shaking the test table and large vibrations obtained by violently shaking the test table.

We are interested in two specific results from this experiment. First, we want to see that the sensor readings are proportional to the type of vibration applied to the experimental rig. Second, we want to see how the sensor readings vary in relation to height. It is known that for tall objects such as buildings, the higher you go, the more intense the effects of vibrations become.

In figure 8 we see the accelerometer readings for the sensor placed on the lowest shelf (sensor ID 4) of the experimental rig taken during each test run. The readings show that while the table is still, the sensor is stable and does not present any relevant activity. As we start increasing the intensity of the vibrations, more and more spikes appear in the readings and they start reverting to normal as the vibrations stop. This shows that the Sparrow v4 sensors can reliably record the intensity of an event.

The other 3 graphs: 11, **??**, 9 show the reading taken from the other sensors (IDs 7, 6 and 5). In the experimental setup, sensor ID 7 was placed above sensor ID 4, making it the second lowest. Then, sensor ID 6 was placed and the, at the highest level, sensor ID 5. The graphics show that the higher the sensor was placed, the interval between spikes near 2G increases and the amplitude of the readings also increases, sometimes going above 2G.

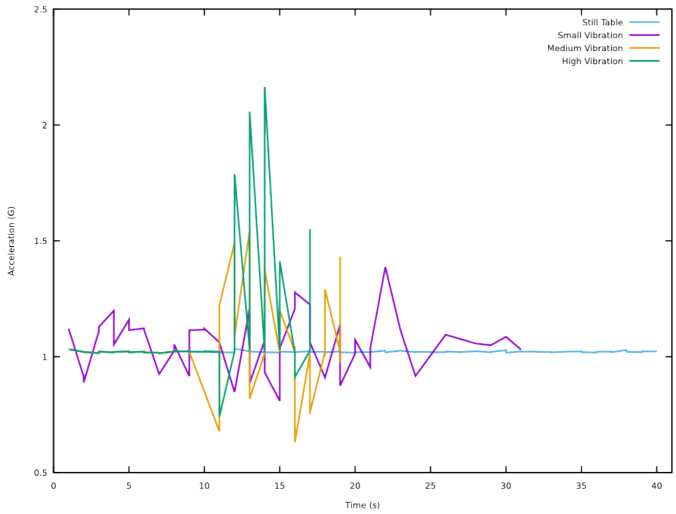

Figure 8. Results for sensor 4 at different intensities

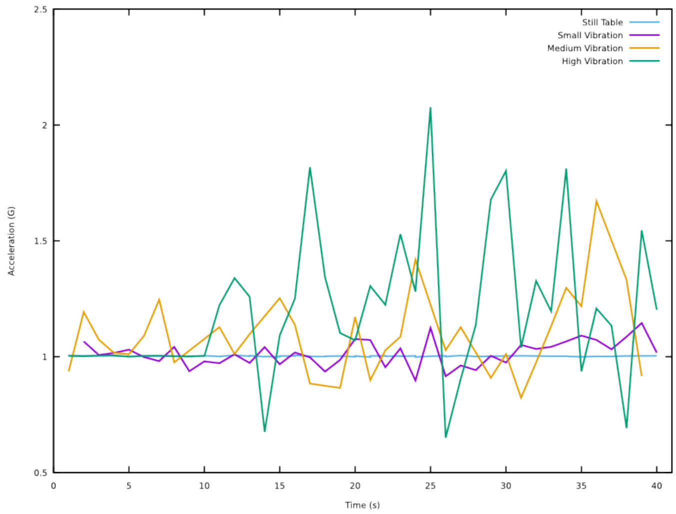

Figure 9. Results for sensor 7 at different intensities

Another observation can be made regarding the calibration step. As it can be seen in **??**, while the normal value for the other sensors is around 1G, sensor 6 is slightly below this value. This happens because not all IMU modules are identical by fabrication, and it must be taken into account when interpreting the data. It also shows why the calibration step is important and necessary.

In figure 12 we see the accelerometer readings for all 4 sensors taken during the same test run. The data from all the sensors shows that the experimental setup is experiencing vibrations. However, it can be noticed that the readings from the sensors placed near the top of the table have a greater amplitude. This shows that, as we theorized initially, the sensor placed closer to the top level will record a higher level of vibration and movement than those placed near the bottom.

One final test performed with the sensors on the shake table was to place them in the middle of a shelf, instead of placing them on the side. In theory, if the material is too elastic or the structure is not properly built to absorb shocks, its weakest point would be in the very middle. This means that after an intense vibration, the sensors would

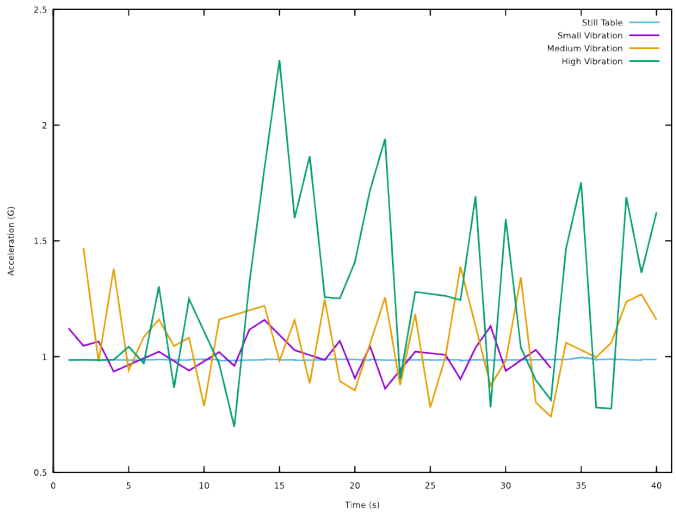

Figure 10. Results for sensor 6 at different intensities

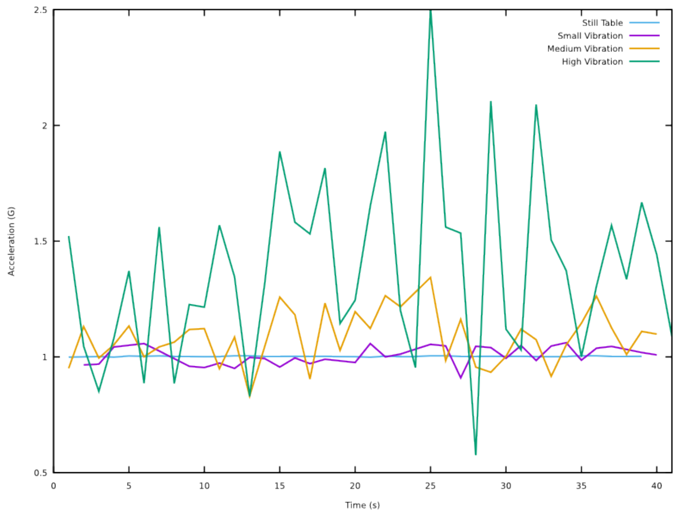

Figure 11. Results for sensor 5 at different intensities

still be getting readings of over 1G even after the source of the vibrations (suppose an earthquake) no longer exists. In figures 13 and 14, we see the results of this experiment as seen at the lowest level (sensor ID 4) and the highest level (sensor ID 5). In the graph, we have kept the sensors on for 40 seconds after shacking the table at different intensities. It can be seen that, for sensor 4, we are still getting readings, but they are nothing too significant, being under 1.5G. For sensor 5, we see that the same applies for small and, to some extent, medium intensities. However, once we get to high intensity vibrations, due to the elastic nature of the table's material, we are still getting readings that reach 2G. This shows that we could potentially use these sensors to detect eventual flaws in the structure of buildings.

6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this paper, through the previously presented experiment, we have shown that the Sparrow v4 wireless sensor node is a viable tool for monitoring earthquake activity. It is also versatile as it can fulfil multiple purposes and

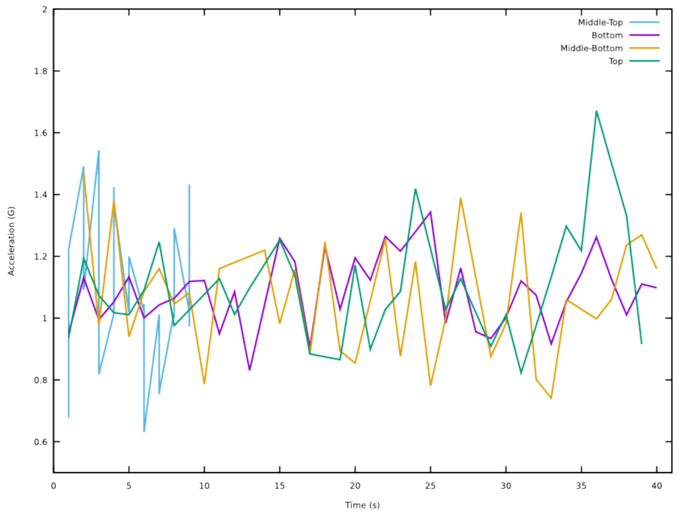

Figure 12. Results for all sensors at the same intensity

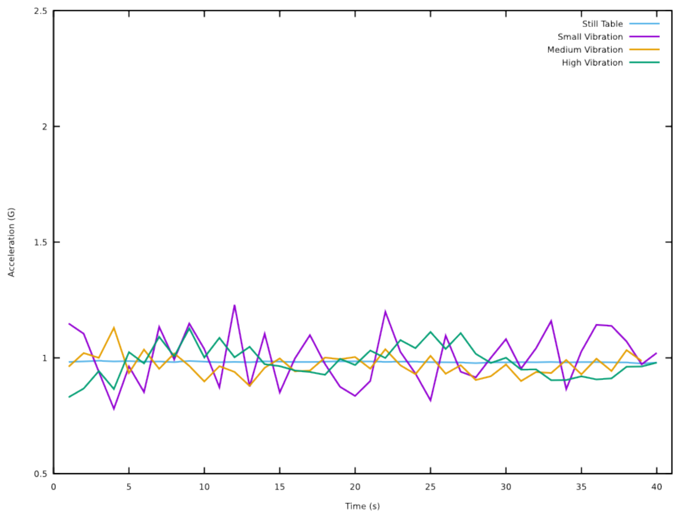

Figure 13. Results for sensors 4 placed in the middle of the shelf

tasks. Sparrow v4 nodes can be placed in key points on a structure to monitor the amount of vibrations which it is exposed to. Alternatively, the nodes can be organized in a wireless sensor network and can be used to monitor seismic activity in certain areas. They can act as a tool which is used to predict earthquakes and warn authorities in case of danger.

The results have shown that the experimental rig is responding similar to a tall building because the lower positioned nodes gather lower amplitude values than the ones located on higher shelves when the table is vibrating. At the end of the simulation, when the table is no longer being shaken and it is naturally vibrating due to previous forces, the higher positioned nodes continue to detect vibrations, as it is most likely to happen in the case of a real building. Even more, the system could detect flaws in various structures and prevent real earthquakes from causing their collapse.

Furthermore, because the sensor nodes are low power, no matter in which type of application they are used, they will

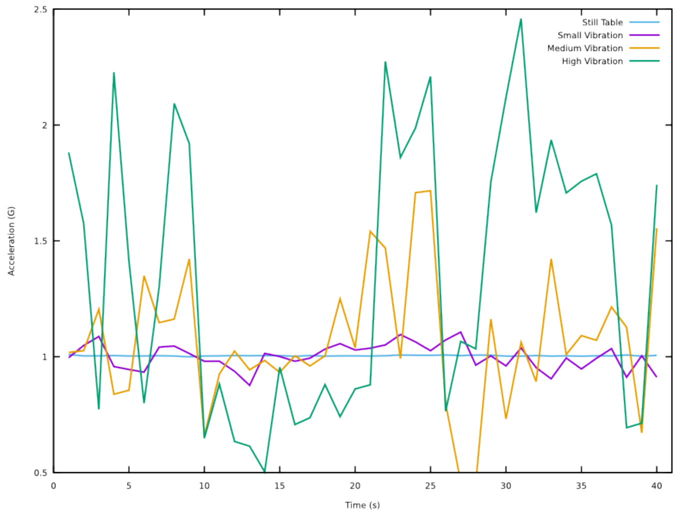

Figure 14. Results for sensors 5 placed in the middle of the shelf

be able to function for prolonged periods of time, which makes them ideal for monitoring environments.

6.2 Future Work

The Sparrow v4 sensor nodes can be further improved by adding energy harvesting modules to their current design. Allowing them to harvest resources such as solar power can further increase their autonomy and efficiency. Further more, there is the possibility of designing a node which needs even less power to function. This can be achieved mainly by swapping the microcontroller with an Atmel SAM R21, which brings the following advantages compared to the existing one:

- 32 bit architecture instead of 8 bit architecture.
- 256 kB of flash instead 128 kb of flash. 150k flash endurance instead of 50k , and 16k eeprom emulation with 600k write cycles endurance instead of 4k eeprom with 100k write cycles. This will allow more data to be saved more often and bigger programs to be used.
- 32 kb of sram instead of. This will allow for higher complexity programs and algorithms.
- Higher operating frequency, 48 MHz instead 16 MHz, while maintaining the same power consumption of 5 mA.
- 70 percent smaller footprint, 32 QFN instead of 64 QFN. This allows for smaller nodes that can be mounted more easily.
- Small improvement in transceiver's power efficiency and transmission power, 4 dB instead of 3.5 dB.
- 12 bit ADC instead of 10 bit ADC for improved sensor reading accuracy.

Another component which can be swapped is the accelerometer. There are models which have a consumption of only 6uA for a 50Hz ODR. Howver, the trade-off for these changes would be a sight increase in the cost of the nodes.

ACKNOWLEDGEMENTS

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